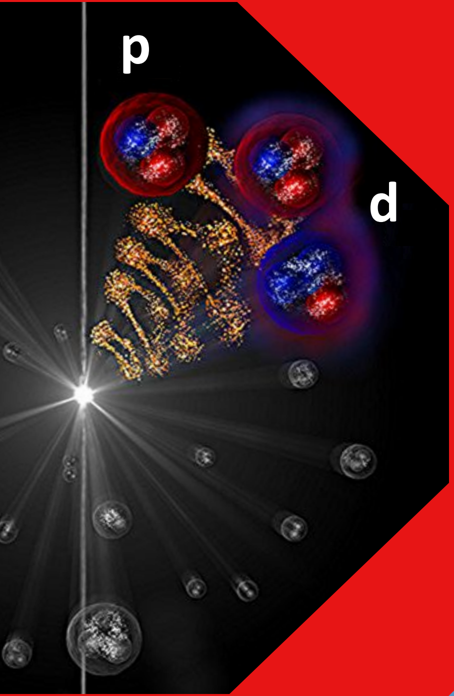
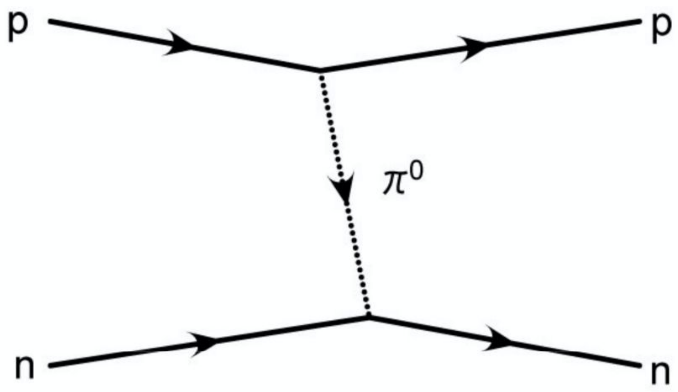


Exploring the Strong Interaction of Three-Body Systems at the LHC

Otón Vázquez Doce (INFN - LNF)
LNF General Seminar, December 11th, 2024

Hadron-hadron strong interactions

Residual strong interaction among hadrons



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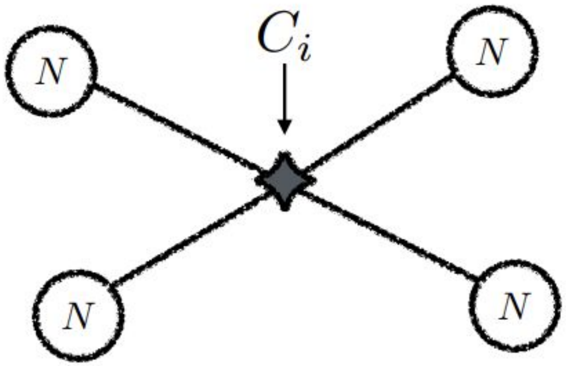


$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$

<u>Effective theories (EFT)</u>

- **Hadrons as degrees of freedom**
- **Low-energy EFT coefficients constraint by data**

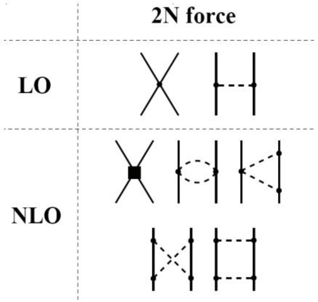
Chiral Effective Field Theory (χEFT)

χEFT allows us to derive nuclear interactions with a expansion on Q/Λ_χ, with $Q \sim m_\pi$, $\Lambda_\chi \sim 1$GeV

S. Weinberg, Nuclear Physics B363, 1 (1991) 3-18

Chiral expansion:

- At **LO two-nucleon forces** are given by one-pion-exchange + NN contact terms determined from the low-energy NN scattering data



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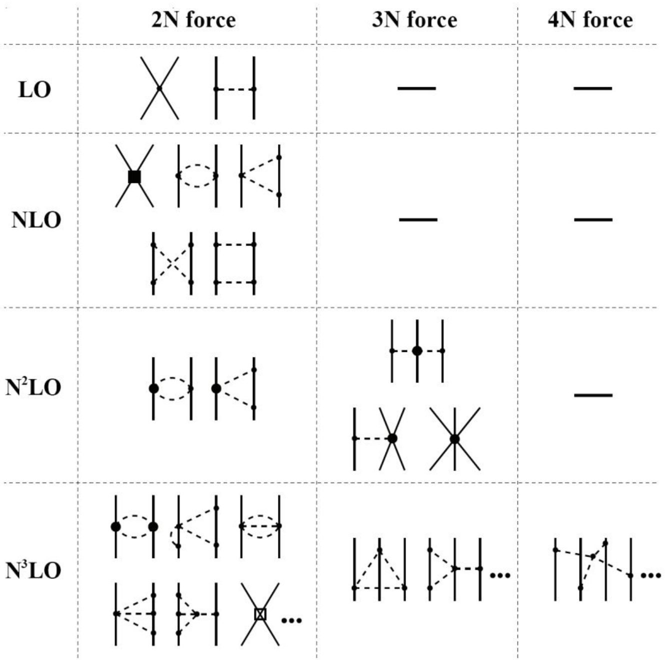
Chiral expansion:

- At **LO two-nucleon forces** are given by one-pion-exchange + NN contact terms determined from the low-energy NN scattering data
- At **next-to-next-to-leading** order first contributions of **three-nucleon-forces arise**

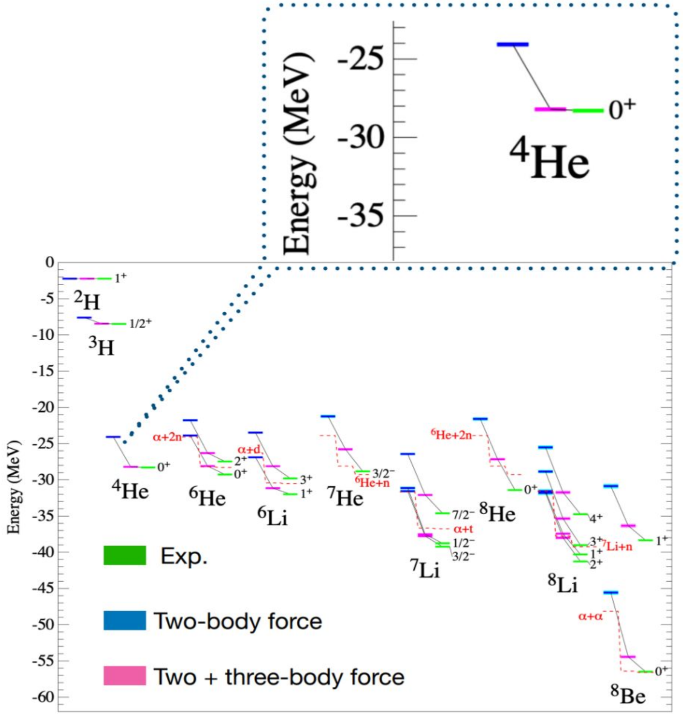


Need of inclusion of many-body interaction

Fundamental ingredient for the study of the nuclear structure

- **Three-body forces necessary to describe properties of nuclei and hypernuclei**

S. C. Pieper, R. B. Wiringa, Ann. Rev. Nucl. Part. Sci. 51:53 (2001), K. Miyagawa et al., Phys. Rev. C 51, 2905 (1995)



⇒ 3-body interaction contributes sizeably (10-20%) to the binding energies of light nuclei

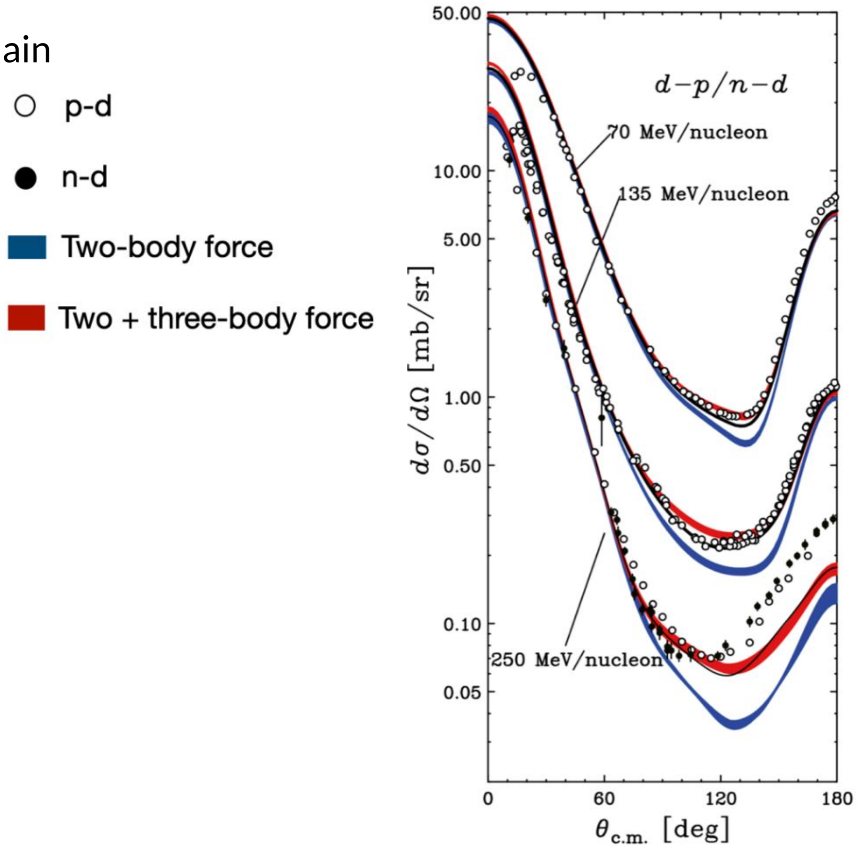
otonvd@cern.ch

Need of inclusion of many-body interaction

Phenomenological 2N + 3N potentials needed to explain nucleon-deuteron scattering observables

K. Sekiguchi, Few-Body Syst 60, 56 (2019)

- 2N: Argonne v18 potential
- 3N: Urbana IX potential



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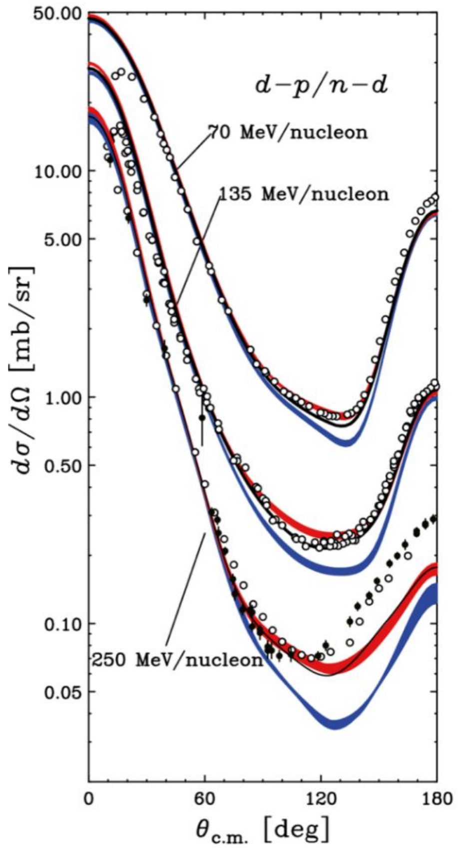


Currently theory is anchored to properties of nuclei, hypernuclei and scattering data

→ Light nuclei average inter-nucleon distance ~2 fm (higher for hypernuclei)

⇒ **3BF become more relevant at smaller distances/higher densities**

Many-body interactions in dense nuclear matter

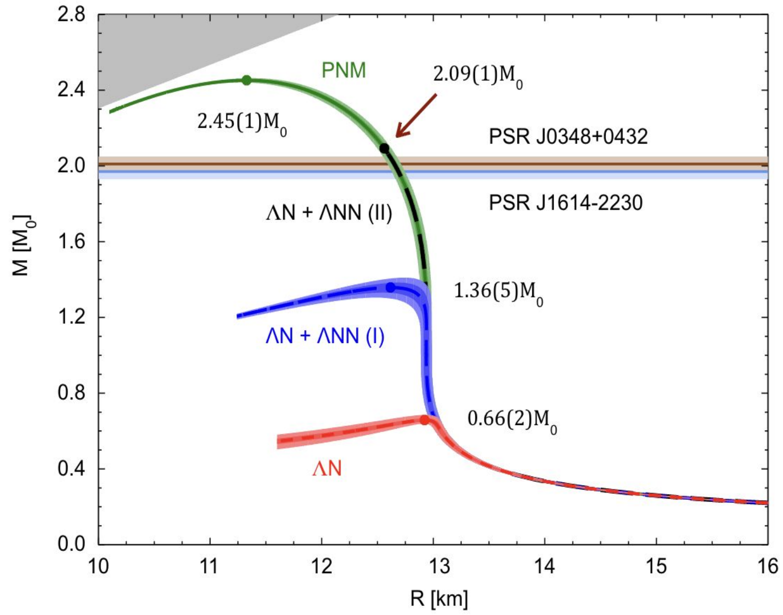
The high densities reached in the core of **Neutron star (NS)** make energetically favorable the appearance of hyperons (reduction of fermi energy)

Radius-Mass relationship:
Tolman-Oppenheimer-Volkoff equations starting from a certain Equation of State (EoS) →

⇒ **With only 2-body forces hyperons EoS difficult to reach the 2 solar masses experimental value**

⇒ **NNN and NNΛ interactions** used in the modeling of the EoS of NS

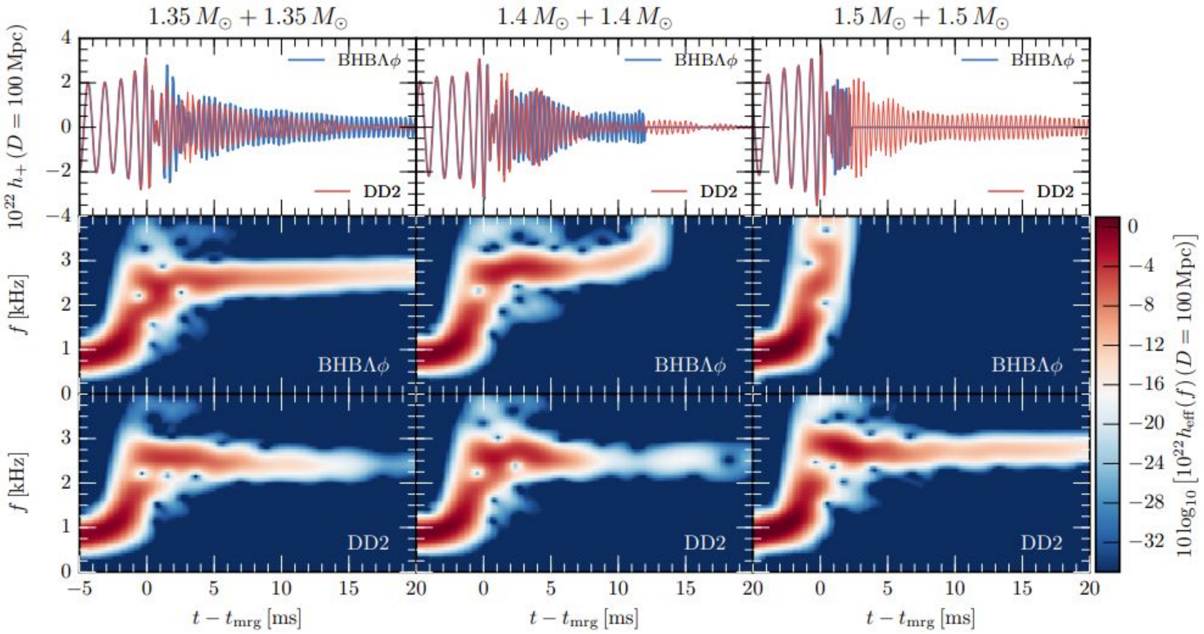
D. Lonardoni et al, Phys. Rev. Lett. 114, 092301 (2015)



Many-body interactions in dense nuclear matter

⇒ Gravitational Wave spectrum from Neutron Star mergers very sensitive to the presence of hyperons in the core

D. Radice et al., ApJL 842 L10 (2017)



...Need to access 3-body interactions also in the strangeness sector...

- **where?**
- **how?**

proton-proton collisions at the LHC

From a high-energy physics facility to nuclear physics

ALICE detector: Central barrel tracking and PID
- Reconstruction of **charged particles**: p, π, K, d

proton-proton collisions at the LHC

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ALICE detector: Central barrel tracking and PID
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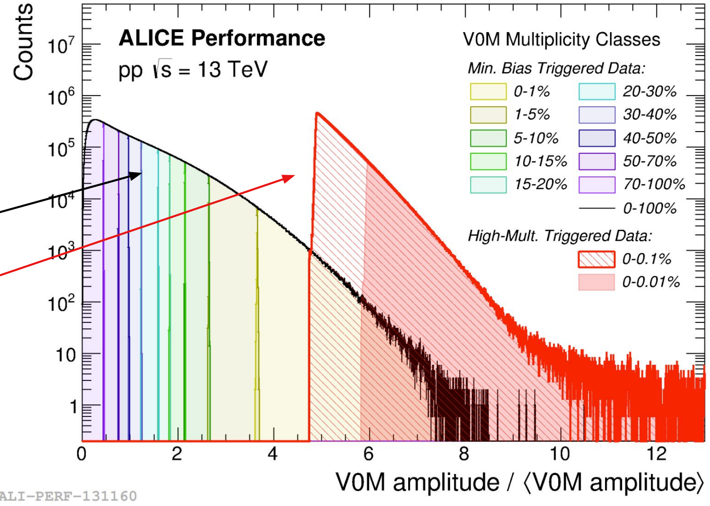
<u>proton-proton collisions at 13 TeV studied by ALICE</u>
Golden sample from Run 2 (2015–2018)
- 1000 M events, <u>high-multiplicity (HM)</u>

minimum-bias events
high-multiplicity trigger



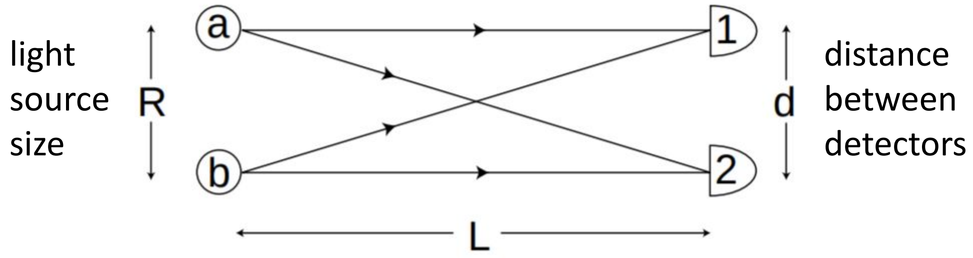
Femtoscopy method in pp collisions

Method defined by HBT interferometry

- based in the **measurement of the correlation function**

$$C(\vec{d}\,) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

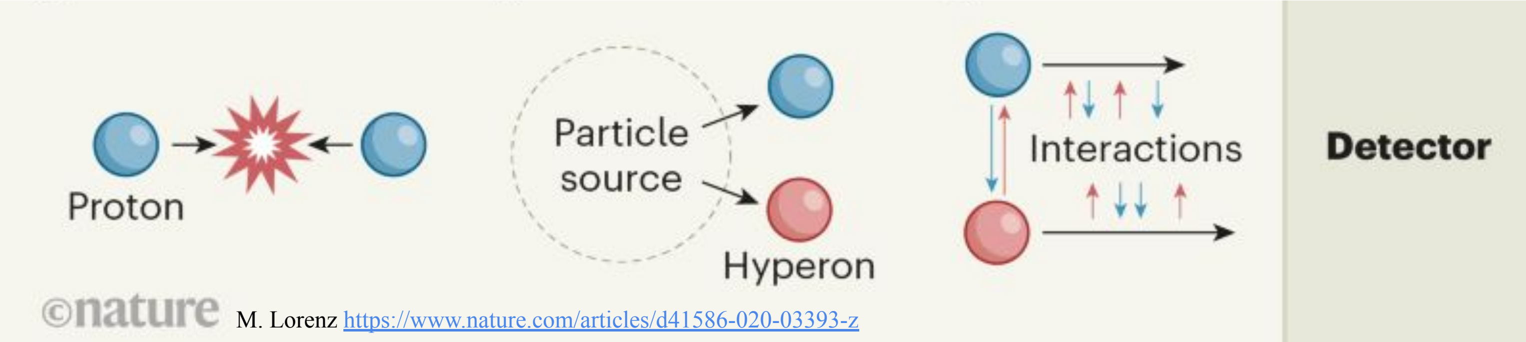
- correlation between intensity signals of telescopes at different distances



Femtoscopy method in pp collisions

Measurement of **the correlation function of two particles emitted a nucleus-nucleus collision**

$$C(\overrightarrow{p_a}, \overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$$



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

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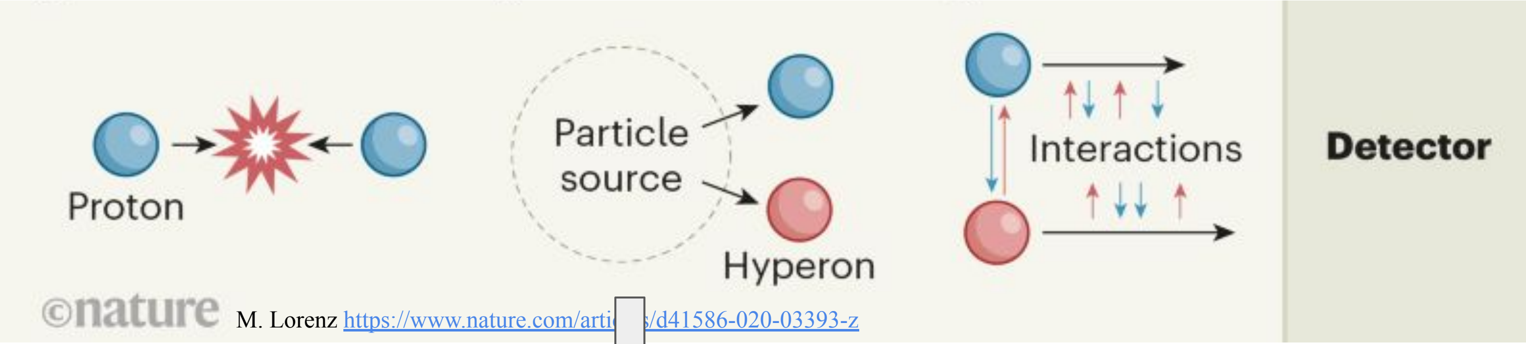

M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

$$S(r) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^2}{4r_0^2}\right)$$

- Gaussian distr. of relative distances (r)
- Width of the gaussian (r_0) → source size

Femtoscopy method in pp collisions

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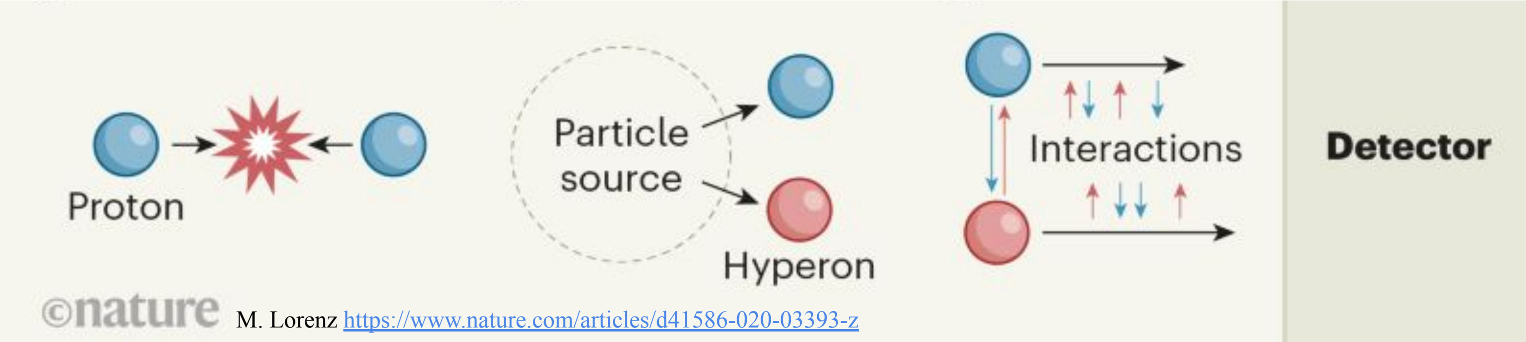
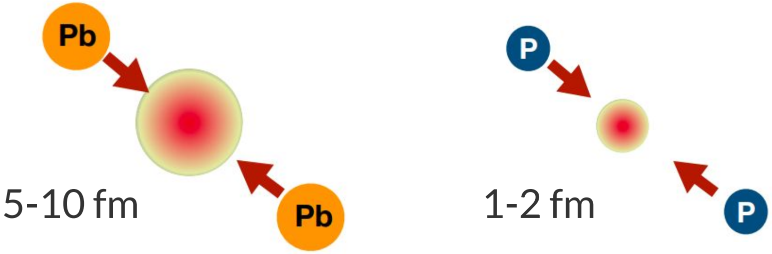


M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

Particle source size:

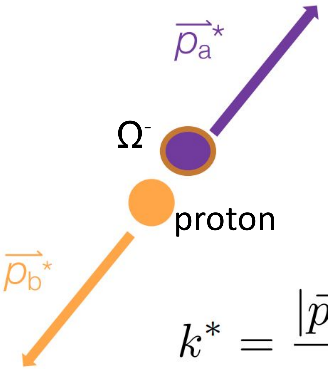


Experimental correlation function

$$C(k^*) = \xi(k^*) \otimes \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

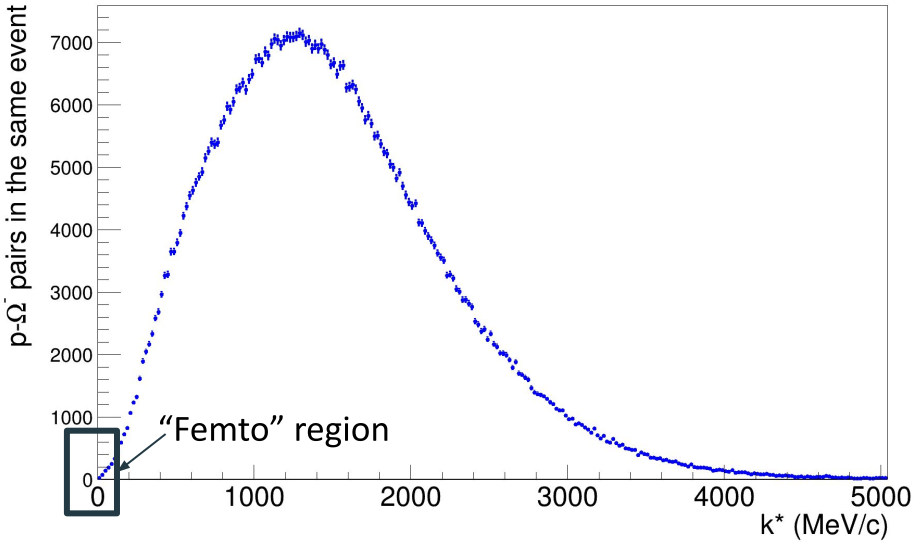
Pairs of particles from same collision

Particles produced in different collisions



$$k^* = \frac{|\vec{p}_a^{\,*} - \vec{p}_b^{\,*}|}{2}$$

in pair reference frame



Theoretical correlation function

$$C(k^*) = \int S(r^*) \left|\Psi(k^*, \vec{r^*})\right|^2 d^3r^*$$

S. E. Koonin, *Physics Letters B* **70** (1977) 43-47
S. Pratt, *Phys. Rev. C* **42** (1990) 2646-2652

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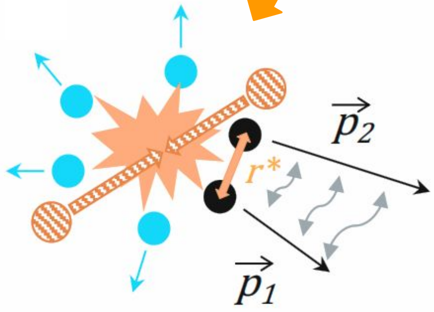

Emission source $S(r^*)$

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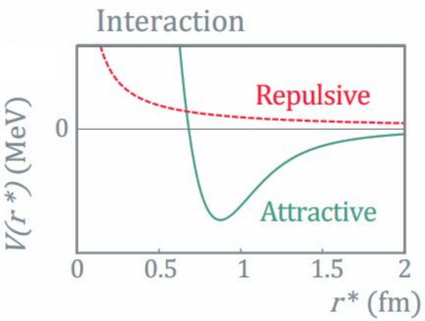

Schrödinger equation D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394

Two-particle wave function $\Psi(k^*,\vec{r^*})$

s-wave asymptotic wave function from scattering parameters (scattering length, effective range) R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770

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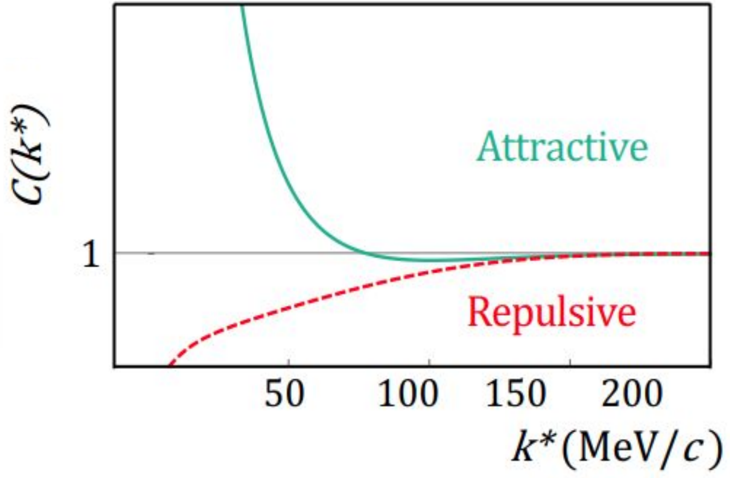

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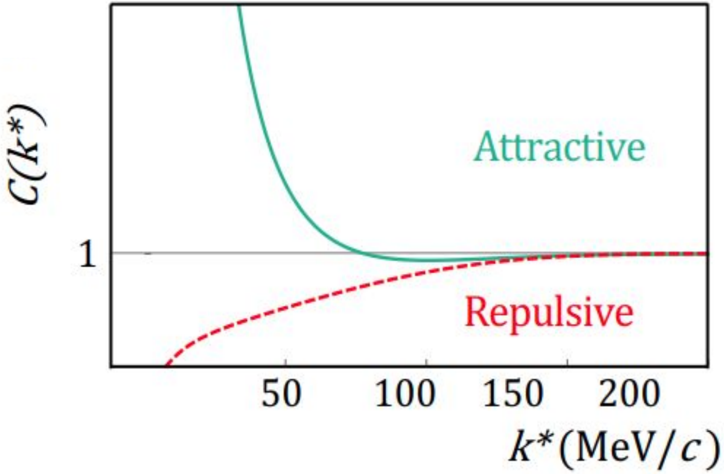


Experimentally:

$$C(k^*) = \xi(k^*) \otimes \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Theoretical correlation function

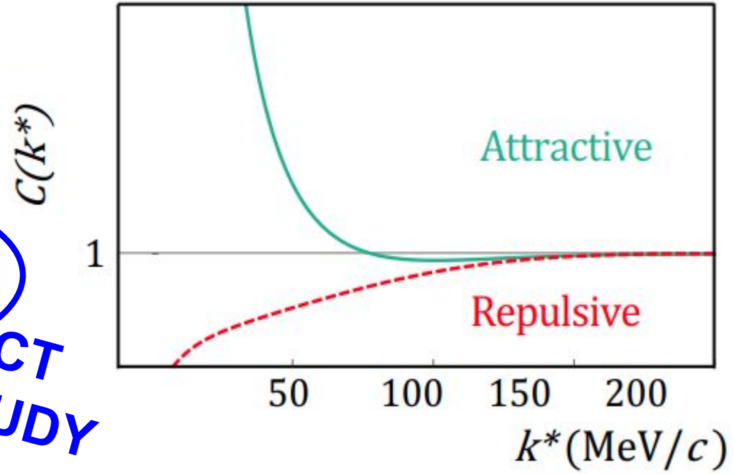
$$C(k^*) = \int S(r^*)\ \left|\Psi(k^*,\overrightarrow{r^*})\right|^2 d^3r^*$$

Emission source $S(r^*)$

KNOWN

Two-particle wave function $\Psi(k^*,\overrightarrow{r^*})$

OBJECT OF STUDY



Experimentally:

$$C(k^*) = \xi(k^*) \otimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

KNOWN

1st step: Setting the source ALICE Coll., Phys. Lett. B 811 (2020) 135849

Ansatz: similar source for all hadron-hadron pairs in small collision systems

The first step is "traditional" femtoscopy: known interaction → determine source size

- p–p interaction: Argonne v18 potential

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ALICE Coll., Phys. Lett. B 811 (2020) 135849

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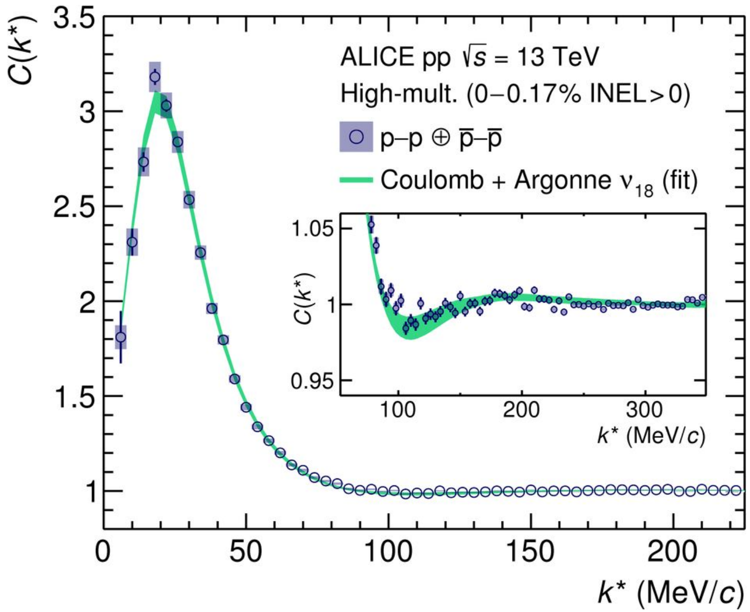


$$C(k^*) = \int S(r^*) \left|\Psi(k^*,\vec{r^*})\right|^2 d^3r^*$$

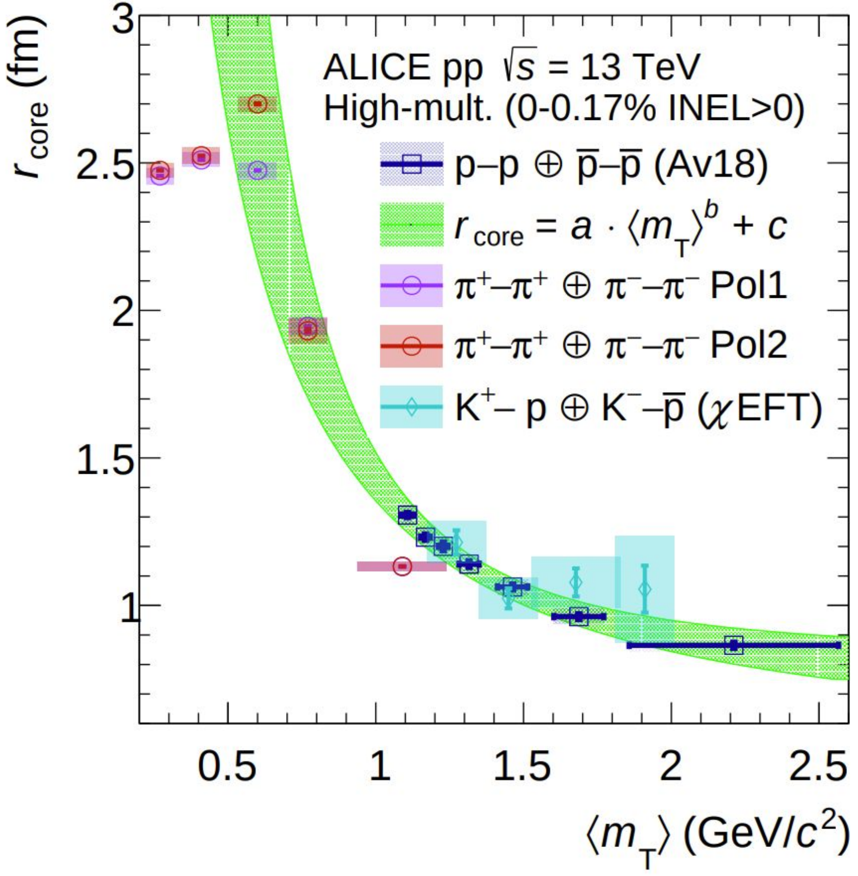
⇒ **Fit of the radius of the source of p-p pairs in p-p collisions.**

The source size (gaussian width) here is the only fit parameter

⇒ **Perform the fit as a function of the transverse mass of the particle pair $\langle m_T \rangle$**

1st step: Setting the source

ALICE Coll., Phys. Lett. B 811 (2020) 135849



The extraction of the source size parameter takes into account the effect of short-lived resonances feeding the final state particles

ALICE Coll., Phys. Lett. B 811 (2020) 135849

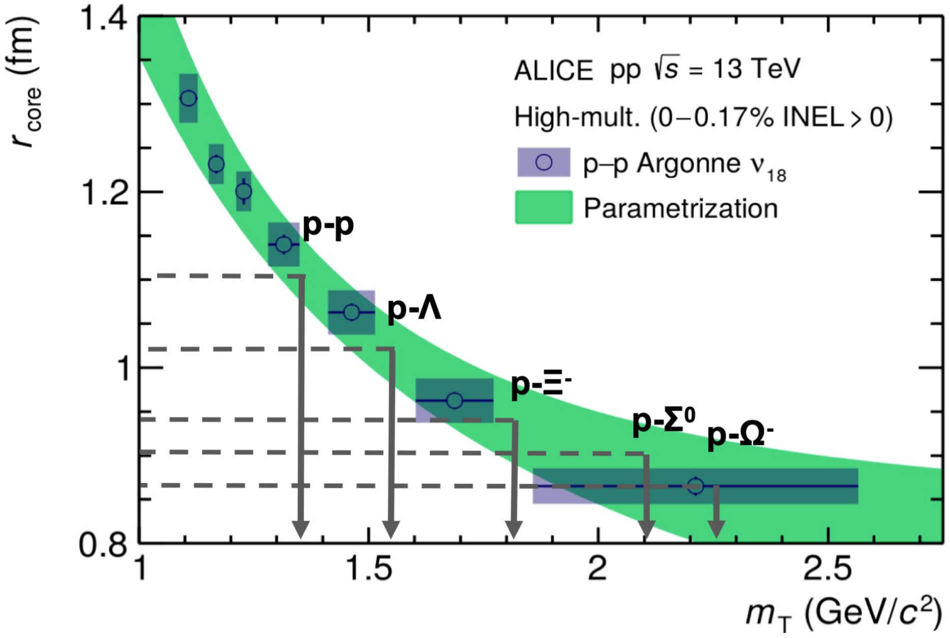
Studying particle pairs with know interactions

⇒ Source size <m_T> scaling confirmed with p-p, π-π and K-p pairs

ALICE Coll.,arXiv:2311.14527 [hep-ph] Submitted to: EPJC

1st step: Setting the source

ALICE Coll., Phys. Lett. B 811 (2020) 135849

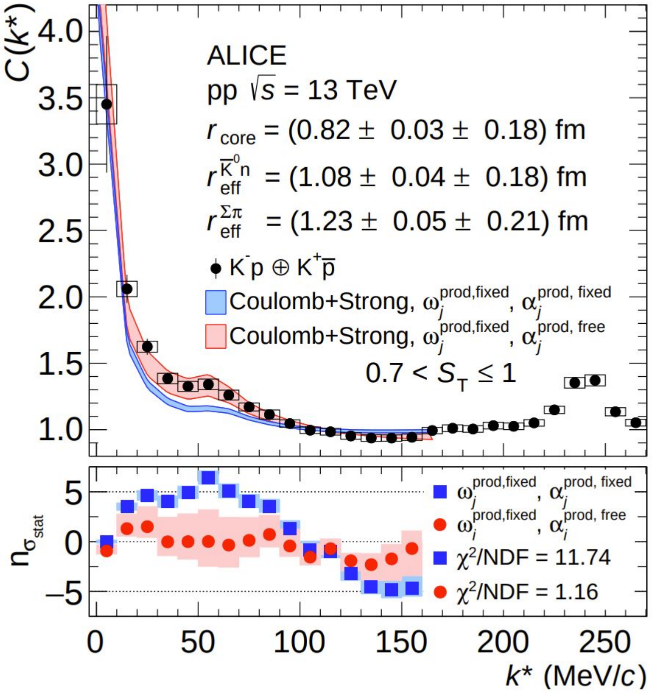


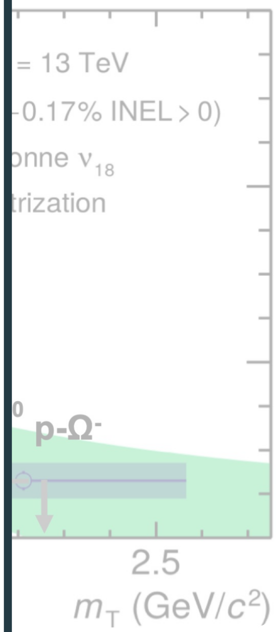
The source size is determined for any given pair <m_T>

…the source

$K^{-}p$ interaction

ALICE Coll. Phys. Rev. Lett. 124, 092301 (2020)
ALICE Coll. Eur. Phys. J. C 83 (2023)





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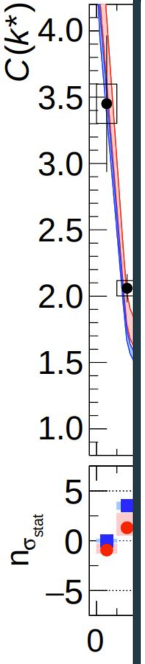
K⁻p interaction

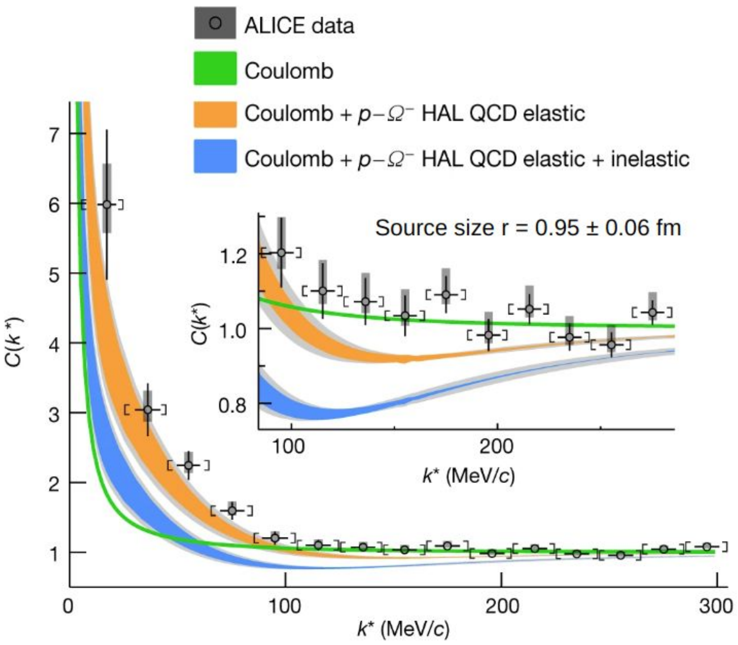
ALICE Coll. Phys. Rev. Lett. 124, 092301 (2020)

ALICE Coll...



pΩ-, pΞ- interaction

ALICE Coll. *Nature* **588**, 232 (2020)

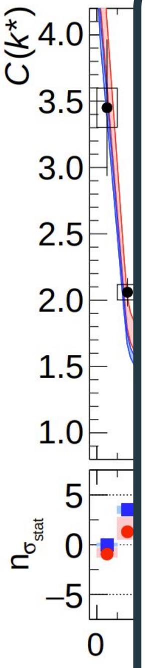


The source size is determined for any given pair <mT>

K^-p interaction

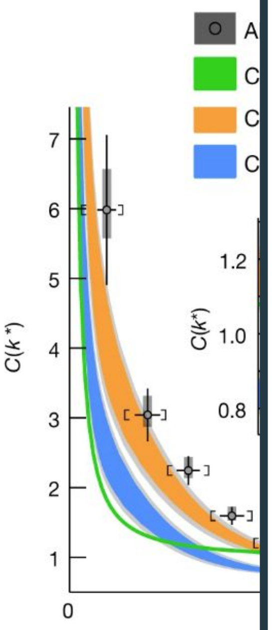
ALICE Coll. Phys. Rev. Lett. 124, 09230

ALICE Coll



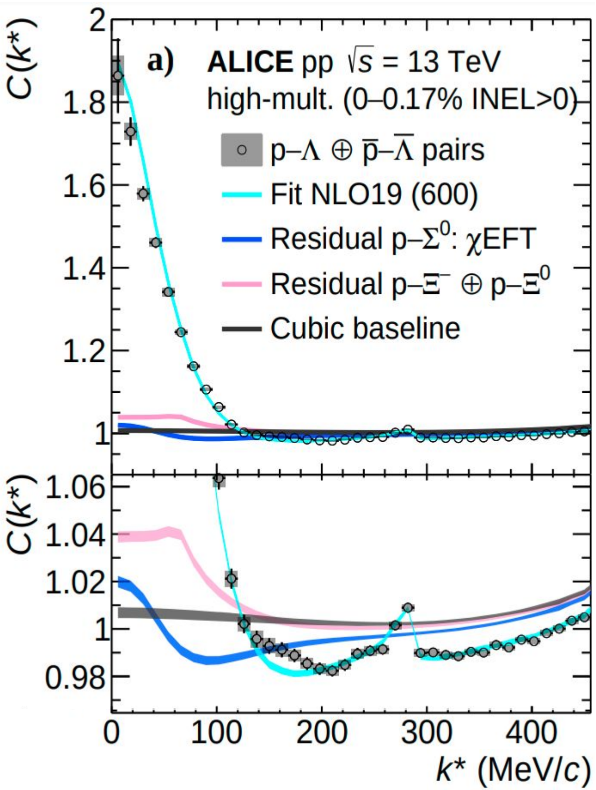
pΩ-, pΞ- int

ALICE Coll. *Na*



pΛ interaction

ALICE Coll. Phys.Lett.B 833 (2022) 137272`



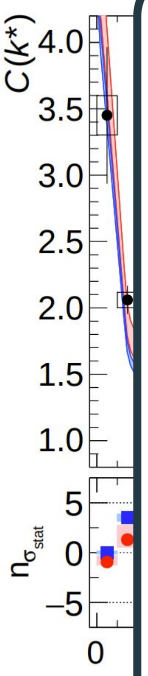
...he source

...e size is determined for any
<mT>

K⁻p interaction

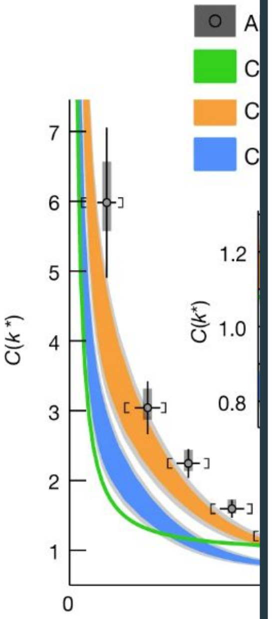
ALICE Coll. Phys. Rev. Lett. 124, 09230

ALICE Coll



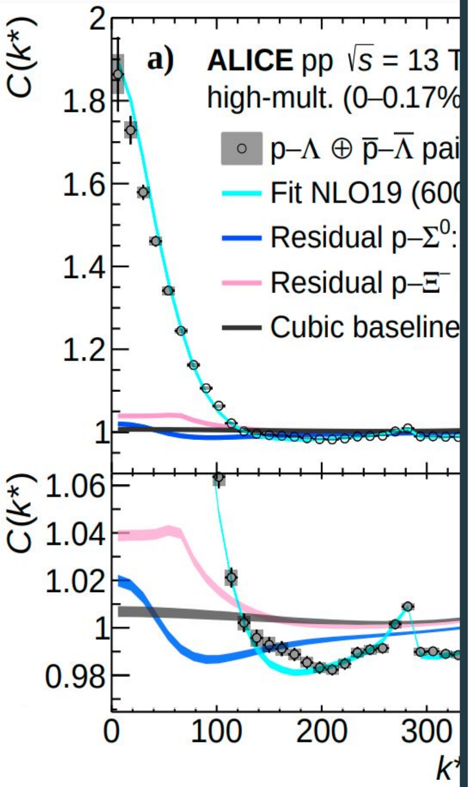
pΩ-, pΞ- int

ALICE Coll. Na



pΛ interaction

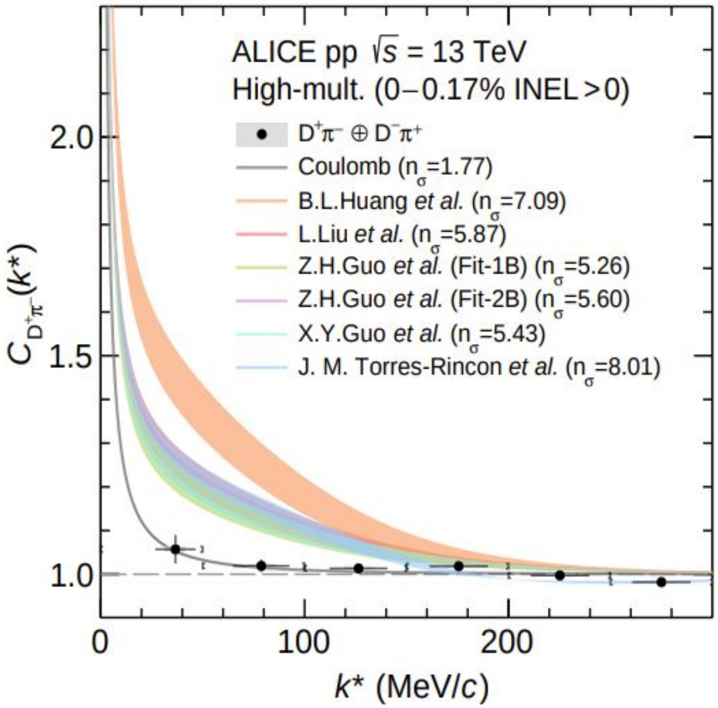
ALICE Coll. Phys.Lett.B 833 (2022)



pD, Dπ, DK, D*π, D*K interactions

ALICE Collaboration Phys. Rev. D 106, 052010 (2022)

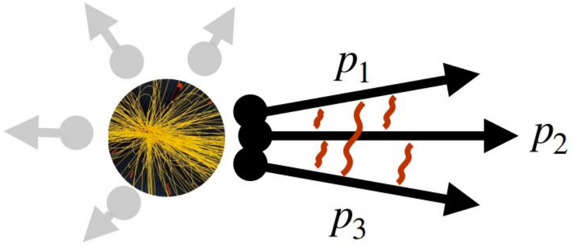
ALICE Coll., arXiv:2401.13541 [nucl-ex] submitted to PRD



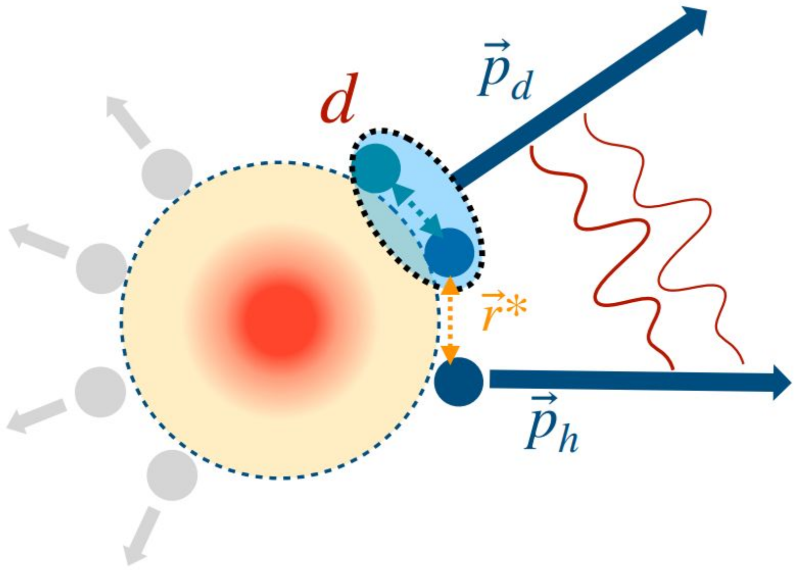
and many other measurements!

Accessing three-body systems with femtoscopy

three-body correlation function



hadron–deuteron correlation

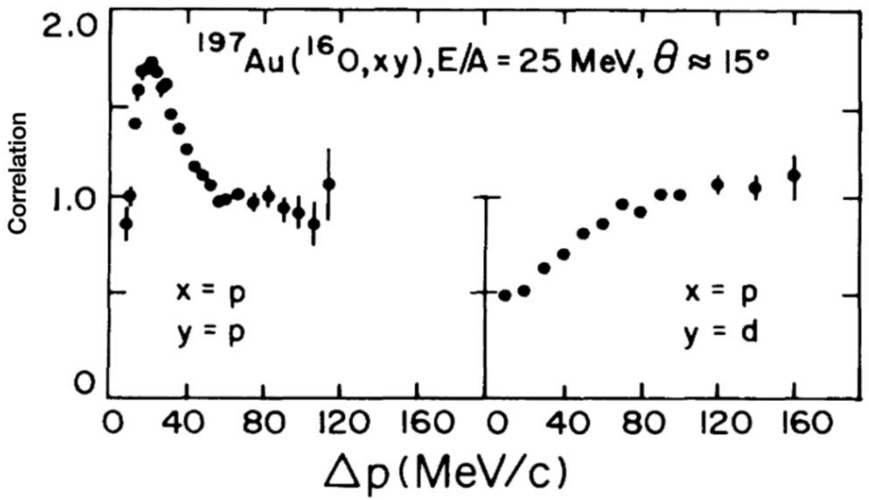


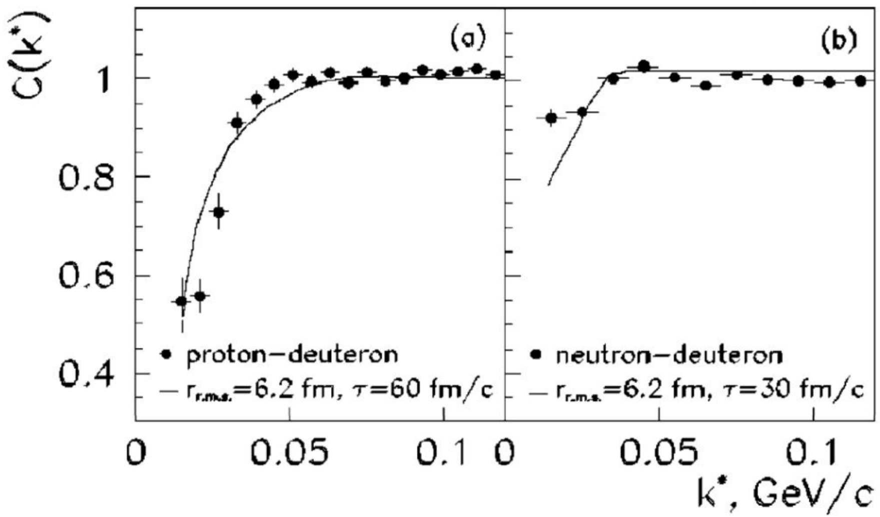
K^+–d and p–d systems

So far... hadron-deuteron correlations

Nucleon-deuteron correlations measured at t very low energy (~ GeV beam energy), fixed target experiments

- Large source size dominant Coulomb interaction
- No full-fledged calculations and unconstrained source distributions

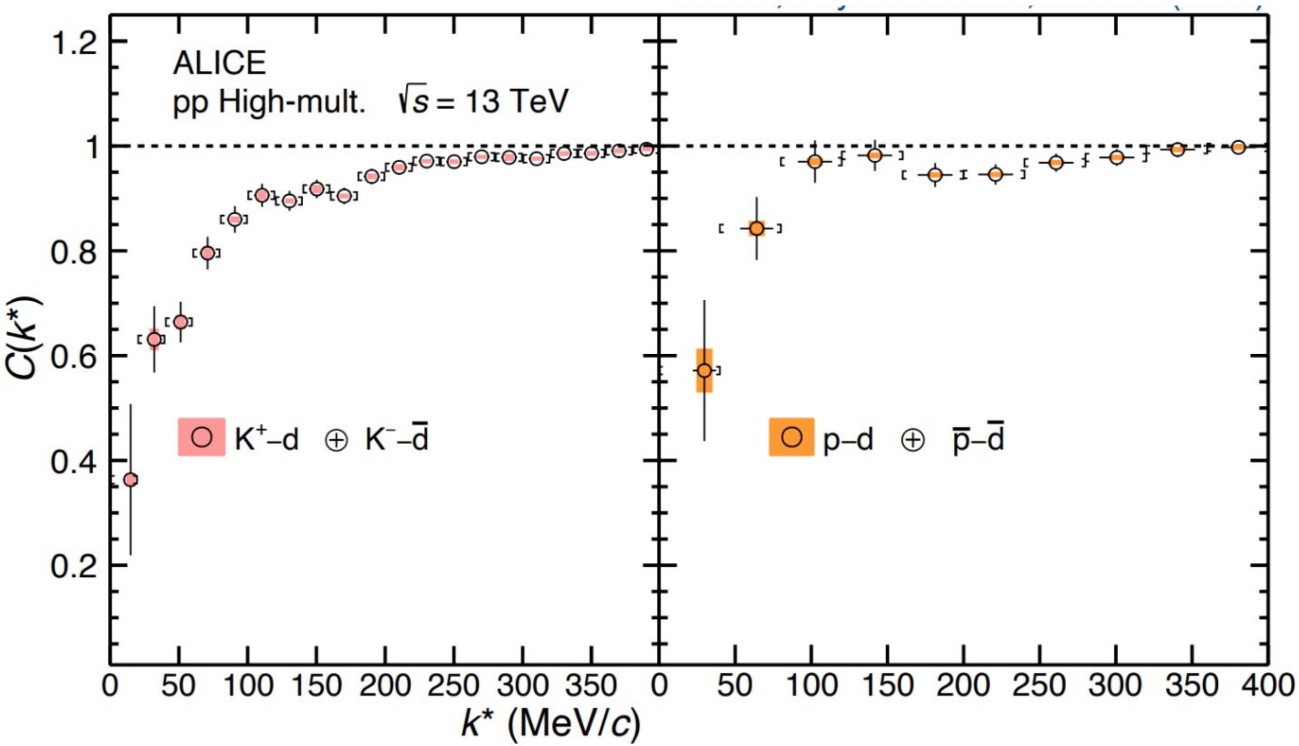




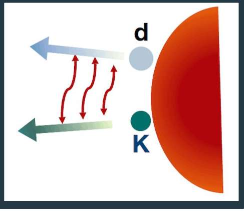
C. B. Chitwood et al, Phys. Rev. Lett. 54, 302 (1985)
J. Pochodzalla et al, Phys. Rev. C 35, 1695 (1986)
J. Pochodzalla et al, Phys. Lett. B 175 (1986)
K. Wosinska et al, Eur. Phys. J. A 32, 55–59 (2007)

Hadron-deuteron correlations in pp collisions at the LHC

ALICE Collaboration, Phys. Rev. X14, 031051 (2024)



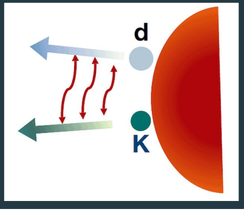
Hadron-deuteron correlation function as a two-body system



ALICE data in pp HM collisions compared with theoretical correlation function considering deuteron as a point-like particle

- Lednický model: s-wave asymptotic wave function from scattering parameters R. Lednický, Phys. Part. Nucl. 40, 307 (2009)

Kaon-deuteron correlation function as a two-body system



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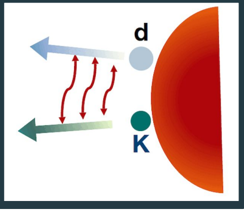
Kaon-deuteron correlation function as a two-body system



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K^+–d correlation in pp HM collisions

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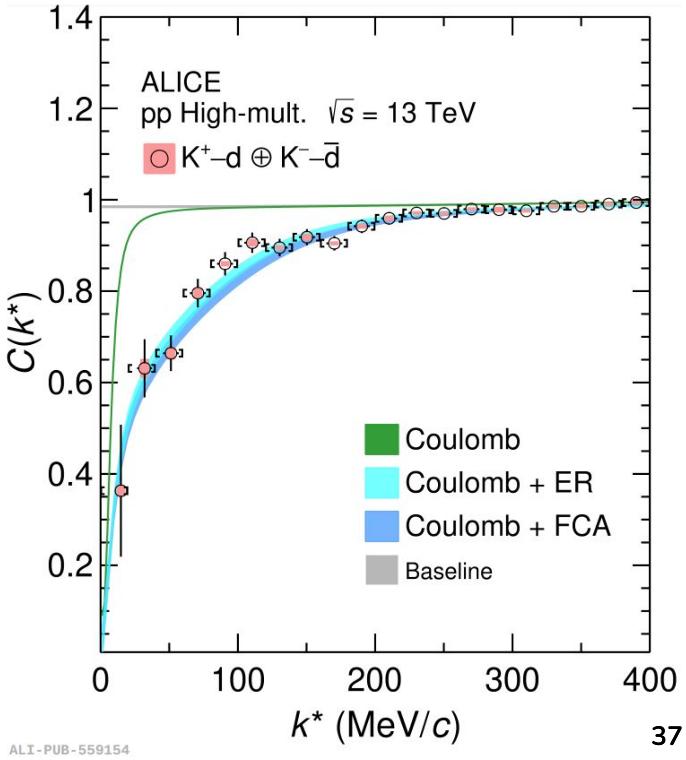
  - ER (effective-range approximation): a_0= −0.47 fm, d_0= −1.75 fm
  - FCA (fixed-center approximation): a_0= −0.54 fm, d_0= 0 fm



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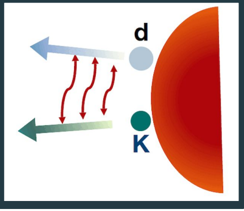

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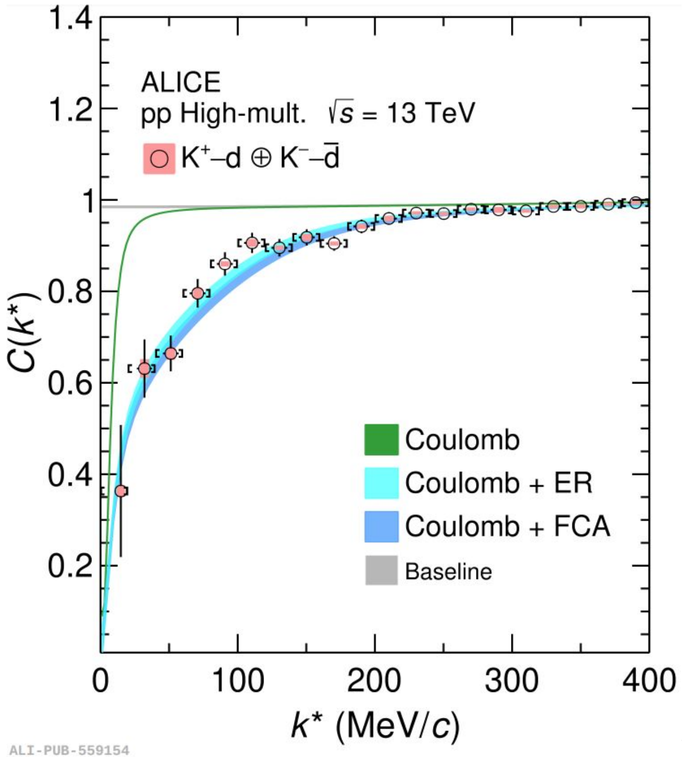
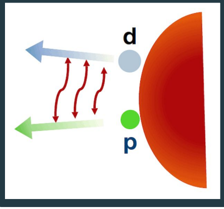
Calculation using Coulomb + strong interaction and small radius describes the data ⇒ **deuterons are produced at very short distances w.r.t. to other hadrons**



ALI-PUB-559154

proton-deuteron correlation function as a two-body system



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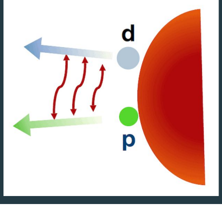

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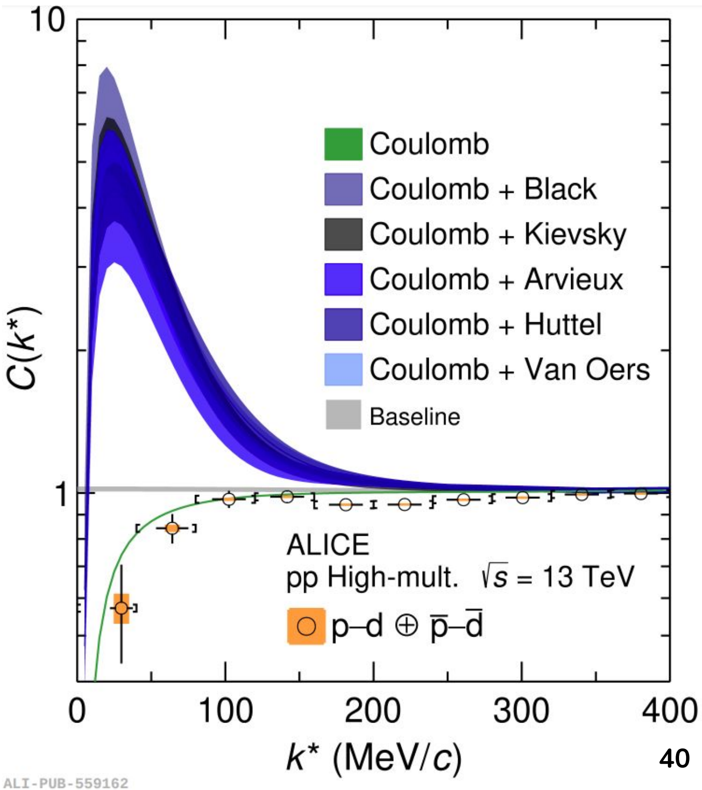
p–d correlation in pp HM collisions

- Source size: r = $1.08^{+0.06}_{-0.06}$ fm from universal m_T scaling
- Strong interaction constrained from the scattering measurements

$S = 1/2$ f_0(fm)	$S = 1/2$ r_0(fm)	$S = 3/2$ f_0(fm)	$S = 3/2$ r_0(fm)	
$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$	Van Oers et al. Nucl. Phys. A 561 (1967)
$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.40}_{-0.10}$	$2.63^{+0.01}_{-0.02}$	J.Arvieux et al. Nucl. Phys. A92 221 (1973)
-4.0	—	-11.1	—	E.Huttel et al. Nucl. Phys. A406 443 (1983)
-0.024	—	-13.7	—	A.Kievsky et al. Phys. Lett, B406 292 (1997)
$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—	T. C. Black Phys. Lett, B471 103 (1999)



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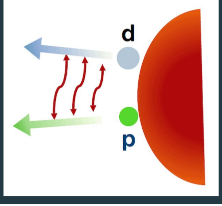

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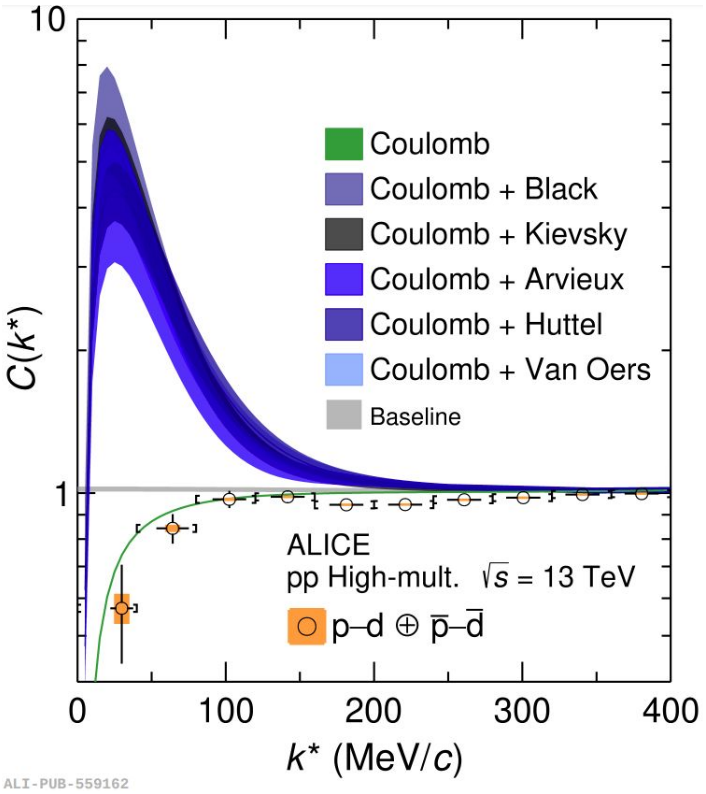
- Strong interaction constrained from the scattering measurements

For p–d, calculations with two point-like particles fail to reproduce the data:

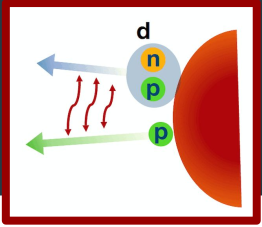
-Pauli blocking for p–(pn) at short distances

-Asymptotic strong interaction not sufficient for small distances

⇒ Need for three-body calculations accounting for p-pn dynamics



p-d correlation function including three-body dynamics



First formulation of the p–d correlation function starting from p–(pn) dynamics that form the p–d state

$$C_{pd}(k^*) = \frac{1}{16\,A_d} \sum_{m_2,m_1} \int \rho^5 d\rho\, d\Omega \left| \Psi_{m_2,m_1\vec{k}^*} \right|^2 \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3}$$

with: $\Psi_{m_2,\,m_1\,\vec{k}^*}$ three-nucleon wave function, p–(pn) to p–d state asymptotically

A_d deuteron formation probability using deuteron wave function

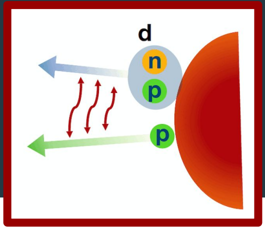
$R_M = 1.43 \pm 0.16$ fm nucleon-nucleon source size in the p–d system from universal m_T scaling

PHYSICAL REVIEW C **108**, 064002 (2023)

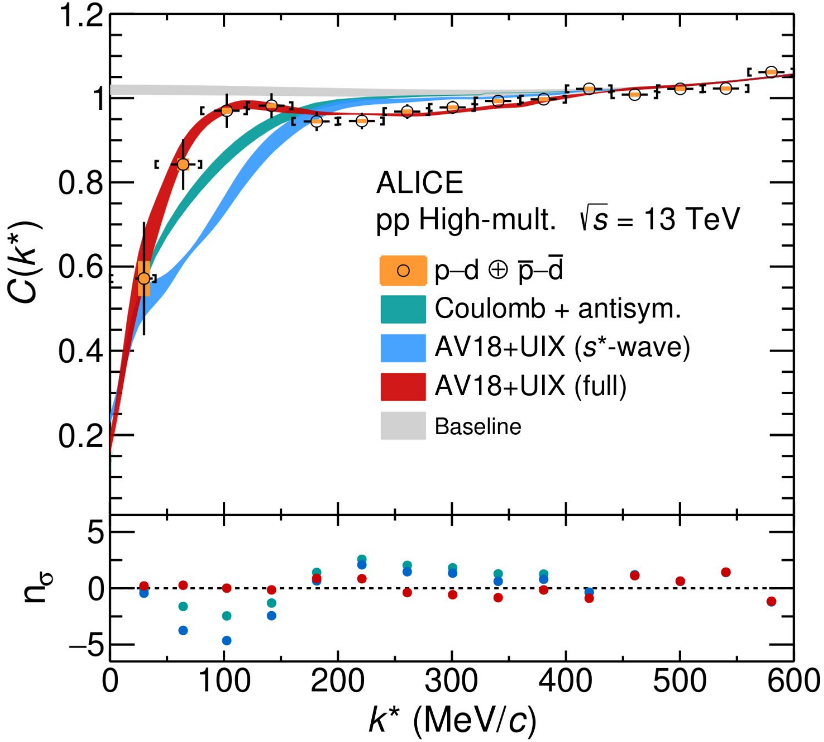
Role of three-body dynamics in nucleon-deuteron correlation functions

M. Viviani,[1,*] S. König,[2,†] A. Kievsky,[1,‡] L. E. Marcucci,[3,1,§] B. Singh,[4,‖] and O. Vázquez Doce[5,¶]

p-d correlation function including three-body dynamics



ALICE Coll., Phys. Rev. X14, 031051 (2024)

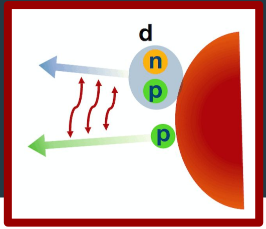


Red curve: full-fledged three-body calculation describes the data by including:

- **2N** force (AV18 potential) **+ 3N** force (UIX potential)
- Calculation up to d-wave

Disagreement when using s-wave only (blue curve) or Coulomb only (green curve) calculations

p-d correlation function including three-body dynamics



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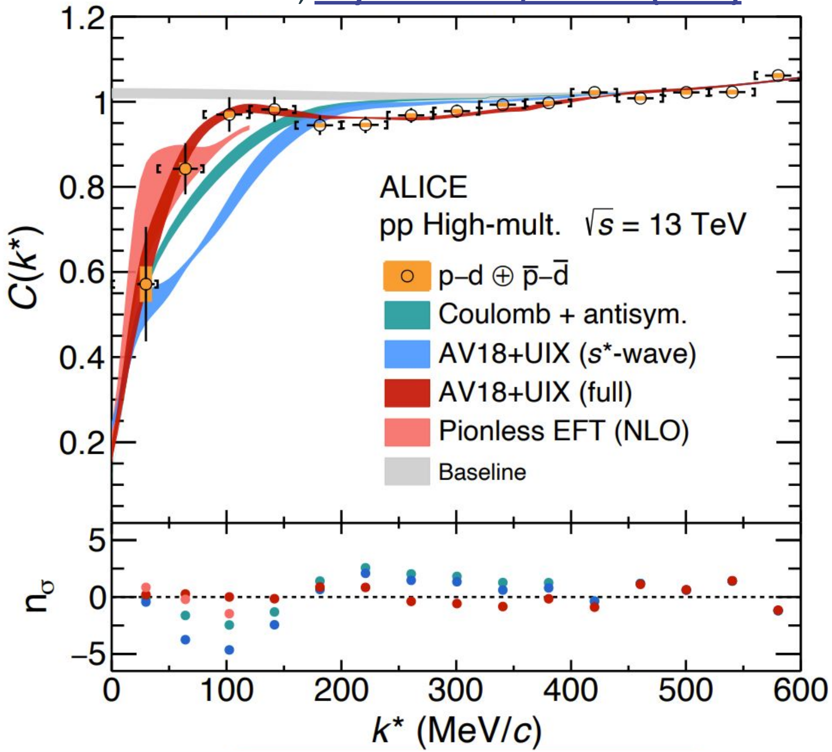

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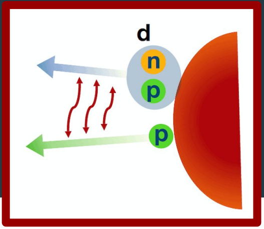
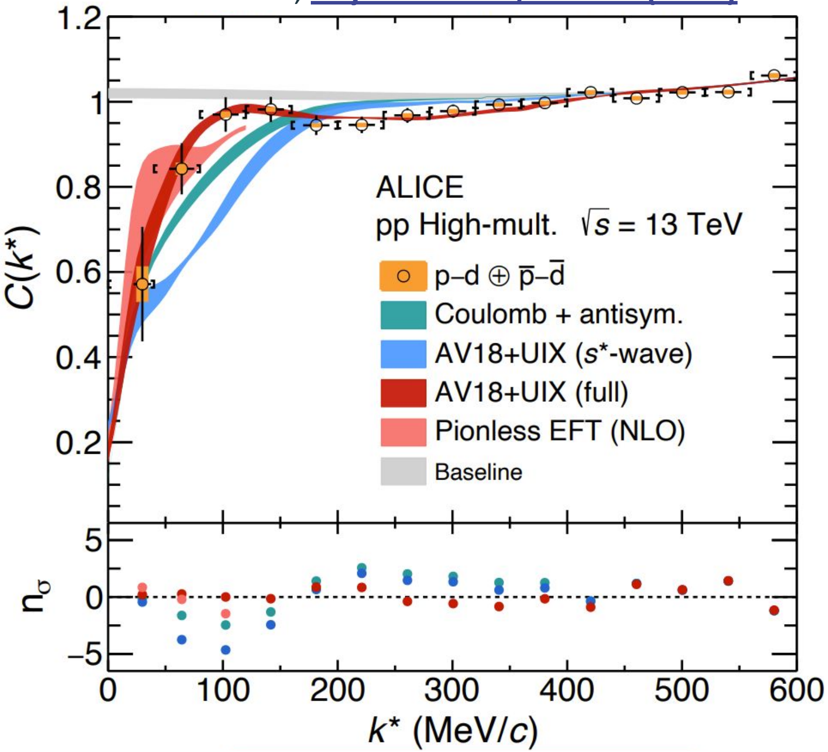


ALICE Coll., [Phys. Rev. X14, 031051 (2024)]



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ALICE measurement of the p-d correlation function sensitive to dynamics of the three-body p–(pn) system at short distances

Open possibilities for the future to study 3BF

Computed correlation function with and without three-nucleon force Urbana IX ⇒

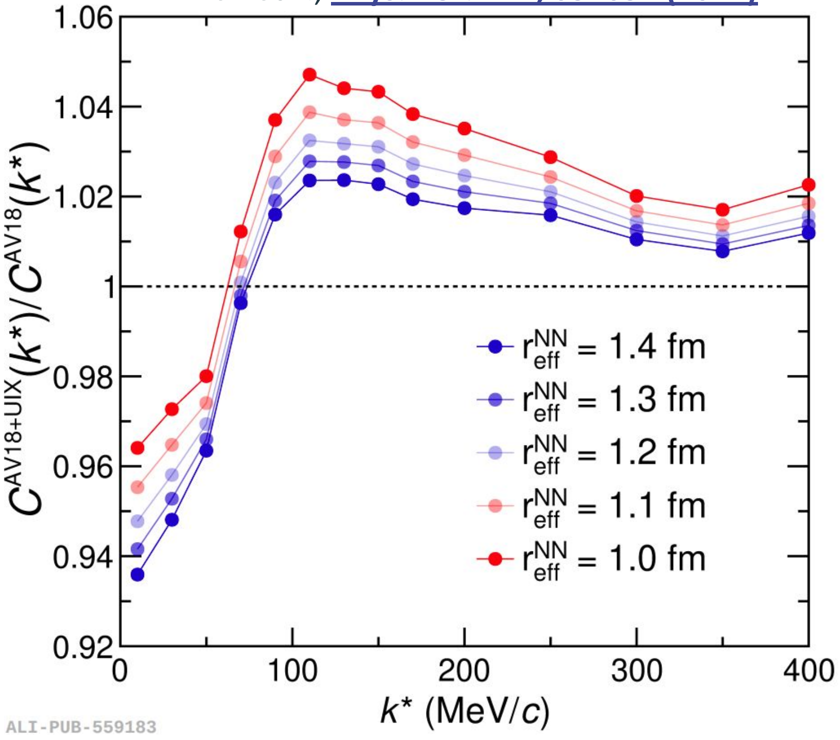
- Up to 5% effect of genuine three-body interaction
- Run 2 limited statistics does not allow to see the effect in the measurement

• LHC Run 3: ~2 orders of increase in pair statistics

- Possibility to perform m_T differential analysis

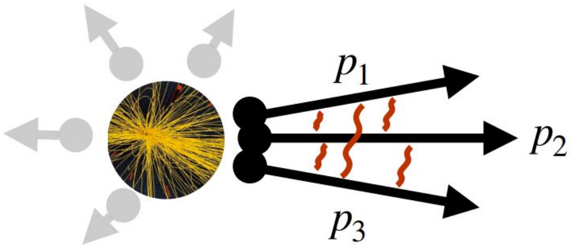
Avenue for the study of hadron–deuteron systems, including charm and strange hadrons!

ALICE Coll., Phys. Rev. X14, 031051 (2024)

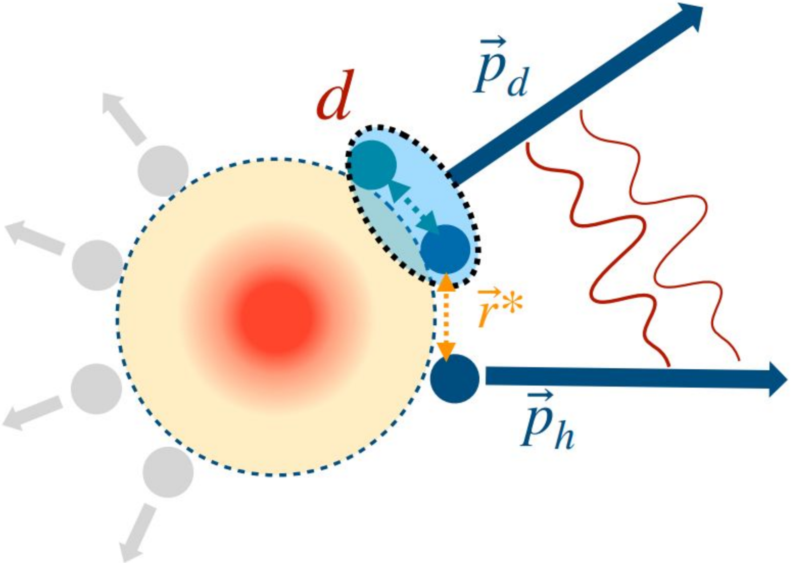


Accessing three-body systems with femtoscopy

three-body correlation function

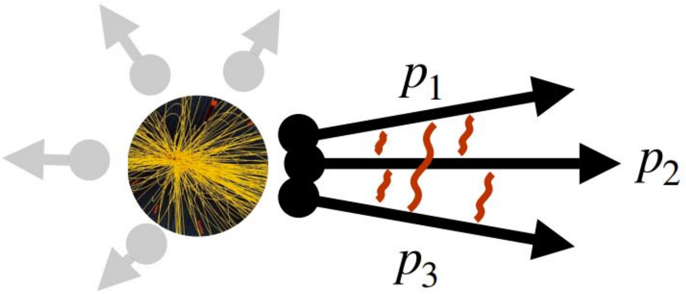


hadron–deuteron correlation



Three-body femtoscopy

Study of three-particle correlations
⇒ Direct access to the genuine three-body forces



Three-particle correlation function:

$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)\,P(\mathbf{p}_2)\,P(\mathbf{p}_3)} = \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

The Lorentz invariant Q_3 is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

with: $$q_{ij}^{\mu} = (p_i - p_j)^{\mu} - \frac{(p_i - p_j) \cdot P_{ij}}{P_{ij}^2} P_{ij}^{\mu}$$

$$P_{ij} \equiv p_i + p_j$$

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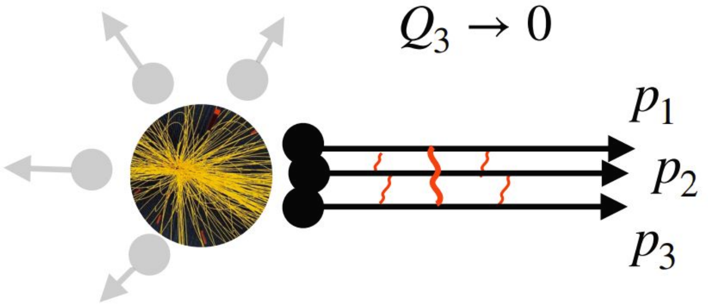

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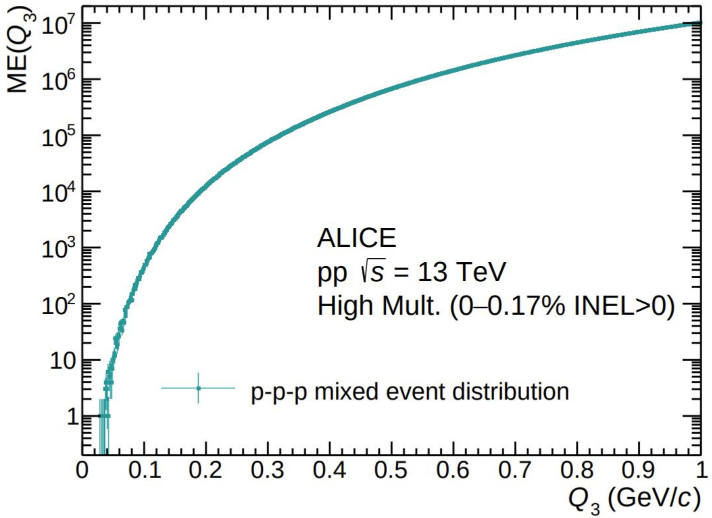
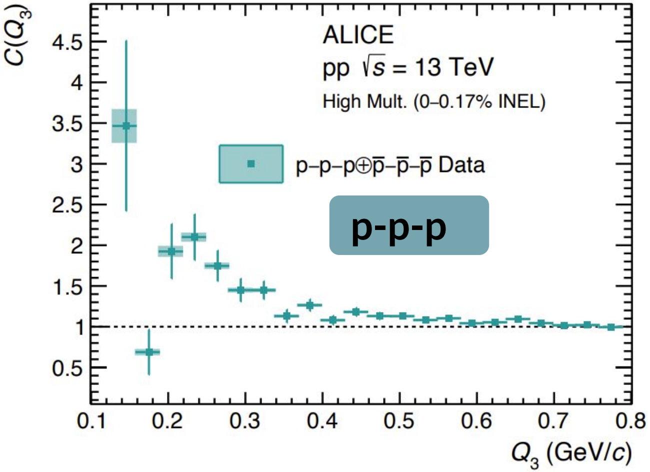
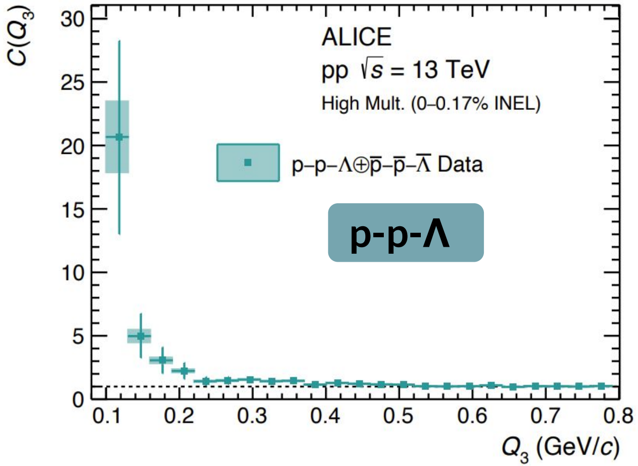


Three-body correlation function

ALICE Coll. Eur. Phys. J. A 59 (2023) 145



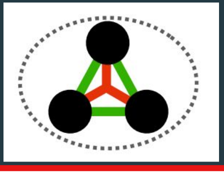


⇒ benchmark, structure of nuclei

⇒ Equation of state of NS containing hyperons

Three-body correlation function:
Full calculations of a three-body system are necessary to interpret the data

Three-body correlation function



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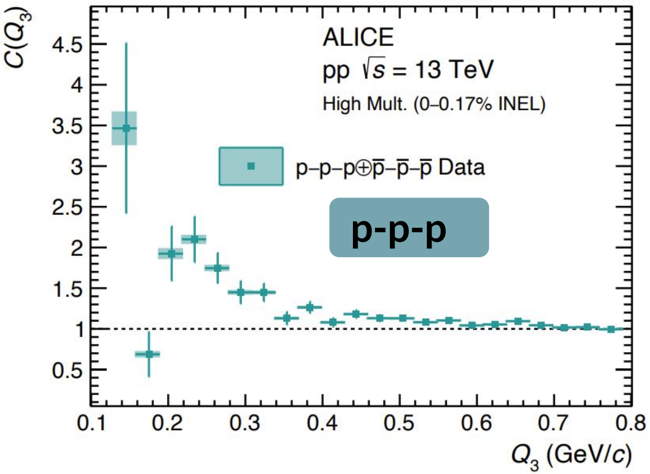
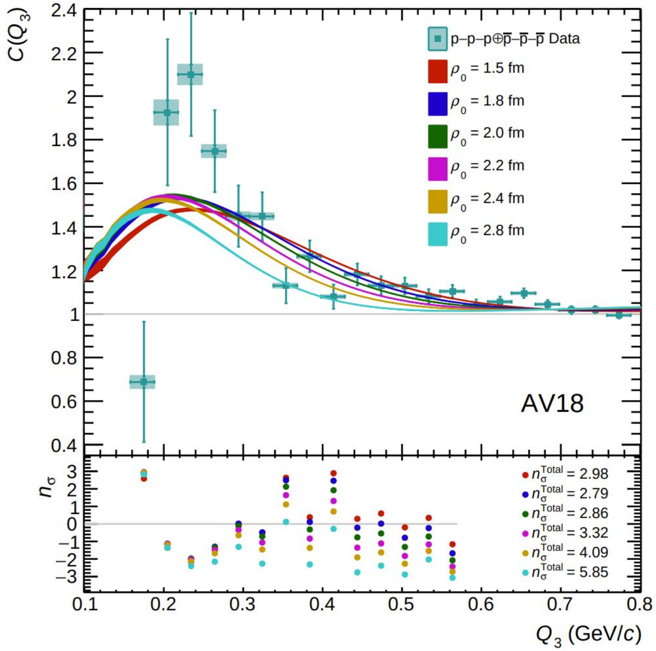


⇒ **benchmark, structure of nuclei**

First calculation of the p-p-p correlation function

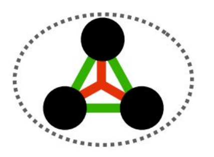
A. Kievsky et al., arXiv:2310.10428 [nucl-th]



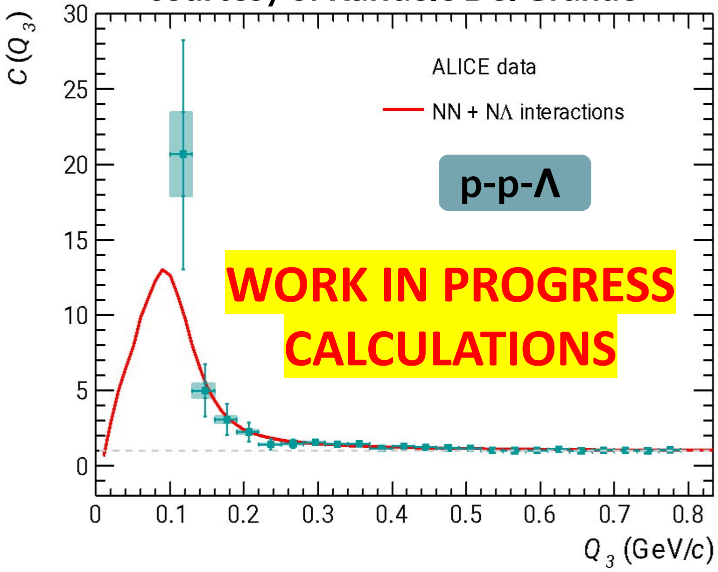
Three-body correlation function:

Full calculations of a three-body system a

Three-body correlation function



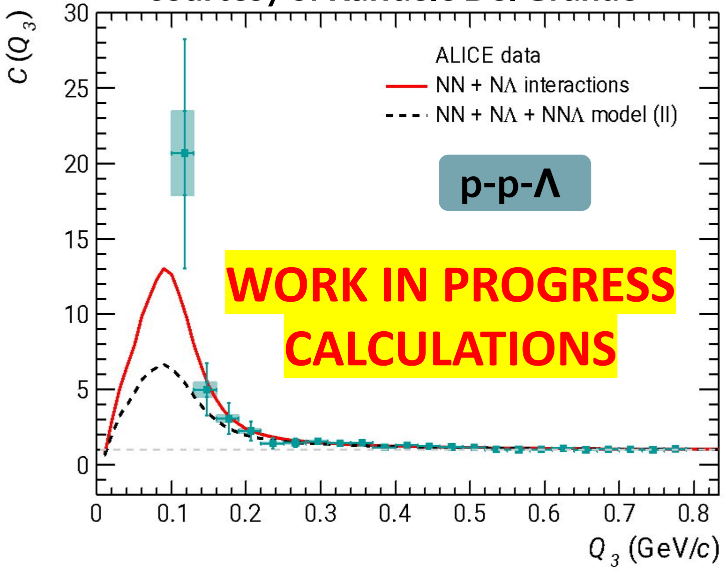
courtesy of Raffaele Del Grande



- Two-body interactions + Coulomb + Antisymmetrization
- Hyper-source radius determined from the two-body p-p and p-Λ sources

Three-body correlation function

courtesy of Raffaele Del Grande

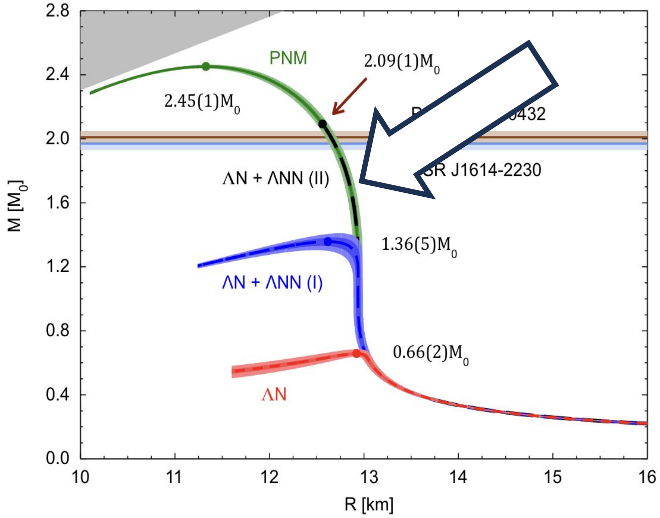


⇒ Two-body interactions + Coulomb + Antisymmetrization

⇒ Hyper-source radius determined from the two-body p-p and p-Λ sources

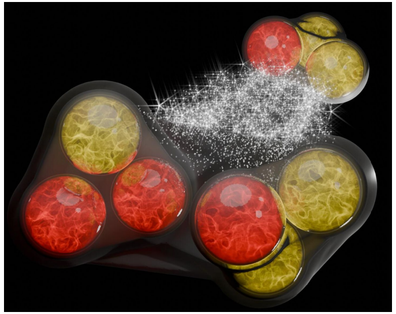
⇒ Inclusion of the ΛNN (model II)

D. Lonardoni et al., PRL 114 (2019)



Summary and outlook

Femtoscopy technique can be used to provide **unprecedented constraints on hadron-hadron interactions…**



- Now ALICE has access to the three-body dynamics via measurements of
  - hadron-deuteron correlations
  - three-body correlation function

- More data = more fun: Present studies within reach with the current **Run 3**
  - **Stats x100!**
  - Three-particle triggers: p-p-Λ
  - Future: ALICE3, a completely new detector will allow to extend our studies to the charm sector